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# Effect of workload setting on propulsion technique in handrim wheelchair propulsion

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## ABSTRACT

**Objective:** To investigate the influence of workload setting (speed at constant power, method to impose power) on the propulsion technique (i.e. force and timing characteristics) in handrim wheelchair propulsion.

**Method:** Twelve able-bodied men participated in this study. External forces were measured during handrim wheelchair propulsion on a motor driven treadmill at different velocities and constant power output (to test the forced effect of speed) and at power outputs imposed by incline vs. pulley system (to test the effect of method to impose power). Outcome measures were the force and timing variables of the propulsion technique.

**Results:** FEF and timing variables showed significant differences between the speed conditions when propelling at the same power output ( $p < 0.01$ ). Push time was reduced while push angle increased. The method to impose power only showed slight differences in the timing variables, however not in the force variables.

**Conclusions:** Researchers and clinicians must be aware of testing and evaluation conditions that may differently affect propulsion technique parameters despite an overall constant power output.

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## 1. Introduction

Measuring propulsion forces and studying propulsion technique of handrim wheelchair propulsion are becoming common in research as well as in some rehabilitation practices [1]. Low mechanical efficiency can explain high physical [2] and mechanical strain [3,4] associated with wheelchair propulsion. However, our understanding of the mechanical load and the role of propulsion technique in handrim wheelchair propulsion is still limited. A propulsion technique with a long push time and a large push angle could increase the mechanical efficiency [5]. Such a propulsion technique can possibly increase performance, reduce the musculoskeletal load and has been associated with lower risk to develop musculoskeletal injuries [6]. With information on force characteristics, magnitude and direction, we could possibly identify the risk factors for overuse injuries [7,8]. It is also important to study propulsion technique when optimizing the wheelchair-user interface, such as seat position or testing new handrim features in manual wheelchair propulsion [9,10].

Over the last couple of years, with the availability of instrumented wheelchairs, considerable research has been done in wheelchair exercise testing concerning force application and propulsion characteristics [11–20]. Results were, however, not always consistent. This might be due to different measuring devices (ergometer vs. ambulant force sensing systems), test conditions (ergometer vs. wheelchair propulsion on a treadmill) or test protocols (time schedule and workload setting (i.e. power output, speed)).

Regarding experiments conducted on a treadmill, several strategies can be chosen to set the workload: by changing speed, changing the slope, or changing the resistance with the use of a pulley system. Researchers have studied the effects of increased speed [21,22] and incline [22,23] on the propulsion variables. The above-mentioned studies found that propelling at a higher speed or incline had an effect on the propulsion variables. However, these effects might not have been caused exclusively by speed or incline itself, since a change in speed or incline also results respectively in a changed power output and resistance, which in itself could have had an influence on the propulsion variables. Veeger et al. and de Groot et al. compared the propulsion variables at the same power output but with different speeds [24,25] and their results showed that some propulsion variables (FEF, propulsion moment) did not change with increased speed at the same power output [24].

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To be able to compare the results of various studies among each other, it is important to know the effect of different workload settings on propulsion technique variables. Where some studies investigated the chosen effect of a higher power output through increasing speed, this study will follow the line of Veeger et al. [24] and will investigate the forced effect of a higher speed (while maintaining constant power and thus by definition lowering the resisting force). This study will compare the forced effect of an incline to propelling on a level treadmill at the same power output. In the latter, the resistance is imposed by a pulley system. It is hypothesized that the effect of a higher speed at a given constant power output influences the propulsion technique variables, namely increases the push frequency and decreases the propulsion force. Further, it is hypothesized that propelling up an incline will lead to a different force application when compared to propelling against the resistance of the pulley system, resulting in the same power output.

## 2. Methods

### 2.1. Subjects

Twelve able-bodied men, all employees at the research department, participated in this study. Inclusion criteria were: male, no experience in wheelchair use and no shoulder pain or recent injuries to the upper extremities. The local ethics committee approved the study and all subjects gave their written informed consent.

### 2.2. Experimental design and data collection

The experiment was performed on a treadmill ("Mill" treadmill, Forcelink B.V., Culemborg, The Netherlands) in a Küschall wheelchair (Küschall K-Series, Küschall AG, Witterswil, Switzerland) with a camber of 6°. The wheelchair had a standard configuration and was not adjusted to the user's body size. The wheelchair was fitted with a SmartWheel (Three Rivers Holdings LLC, Mesa, AZ, USA) on the left side and a dummy wheel on the right side [21].

Kinematics of the hand were measured with a 6-camera infra-red camera system (Oqus, Qualisys AB, Gothenburg, Sweden). Kinematic data collection was synchronized with the SmartWheel at 100 Hz.

Before testing, the subjects were allowed to become accustomed to the wheelchair and the experimental setup. However, they were not instructed how to propel the wheelchair. After the familiarization period, the individual rolling resistance was determined in a separate drag test [26]. This technology was a special purpose development of the Engineering department of the Faculty of Human Movement Sciences of the VU University, Amsterdam, The Netherlands [27]. Based on the rolling resistance, external power output could be regulated with an additional external force, acting via a pulley system on the wheelchair-user combination (Fig. 1). External power output ( $PO_{\text{external}}$ ) was calculated as:  $(F_{\text{drag}} + F_{\text{additional}}) \cdot v_{\text{belt}}$  [28].

To evaluate the effect of speed, the subjects propelled at a constant power output (25 W) with three belt velocities ( $v_{\text{belt}} = 0.83, 1.11, 1.38 \text{ ms}^{-1}$ ) in combination with additional force acting via the pulley system ( $(F_{\text{drag}} + F_{\text{additional}}) \cdot v_{\text{belt}} = 25 \text{ W}$ ).

To evaluate the effect of the method to impose the external power, the subjects first propelled with a constant velocity of  $1.11 \text{ ms}^{-1}$  and increasing inclines (1%, 2.5% and 4%). Subsequently, the same external PO was evaluated through a simulation of the resistance of the three inclines via the pulley system, while the treadmill remained horizontal (Fig. 1).



Fig. 1. Overview of the test setup where the subject is propelling against extra resistance generated by a pulley system.

All test conditions were 1-min exercise bouts during which data were collected during the last 30 s.

### 2.3. Data analysis

From the 30 s recorded during each exercise bout, only complete pushes were used for data analysis. Cadence (number of pushes per minute) was calculated on the basis of the duration and number of the complete pushes in these 30 s by use of a Matlab program (The MathWorks Inc, Natick, MA, USA).

The SmartWheel recorded forces and moments in three dimensions [29] at 100 Hz, these forces were corrected for camber and analyzed in the following global coordinate system:  $F_x = F_{\text{lat}}$ : horizontally inward (the SmartWheel was fitted on the left side of the chair),  $F_y$ : vertically upward and  $F_z$ : horizontally backward. Via the inclination angle of the treadmill, forces were transformed to the global coordinate system. The total force ( $F_{\text{tot}}$ ) acting on the push rim was calculated as the norm of the three force components.

The effective force component  $F_{\text{tan}}$ , which is tangential to the rim, as well as the radial force component ( $F_{\text{rad}}$ ) was calculated from the global force components ( $F_y$  and  $F_z$ ) and the hand position in relation to the wheelchair axis [29]. It was assumed that the second metacarpal was the point of force application onto the rim [24,30]. For all force variables the mean values over the push phases were calculated.

Over each push phase, the fraction of effective force (FEF) was calculated as the ratio between the mean propulsion moment around the wheel axle ( $M_{\text{wheel}}$ ) divided by rim radius ( $r_{\text{rim}}$ ) and the mean  $F_{\text{tot}}$  ( $\text{FEF} = (M_{\text{wheel}} \cdot r_{\text{rim}}^{-1}) \cdot F_{\text{tot}}^{-1}$ ) [24].

Performed power output ( $PO_{\text{performed}}$ ) was calculated under the assumption that equal mean power was produced on the left and the right wheel over time [31]. Therefore power output was calculated as the product of the measured torque and the angular velocity times two ( $PO_{\text{performed}} = (M_{\text{wheel}} \cdot \omega) \cdot 2$ ) [32]. From the mean  $PO_{\text{performed}}$  and the cadence ( $f$ ) in Hertz, the average work per cycle ( $W_{\text{cycle}}$ ) was calculated ( $W_{\text{cycle}} = PO_{\text{performed}} \cdot f^{-1}$ ) [33].

Push time was defined as the time period where the hand exerted a positive torque on the handrim [34]. Cycle time was defined as the period of time from the onset of one push phase to the onset of the next, recovery time as the difference between cycle time and push time. Push time was also expressed as the percentage of cycle time (PTpC). Push angle represents the angle over which positive torque was applied.

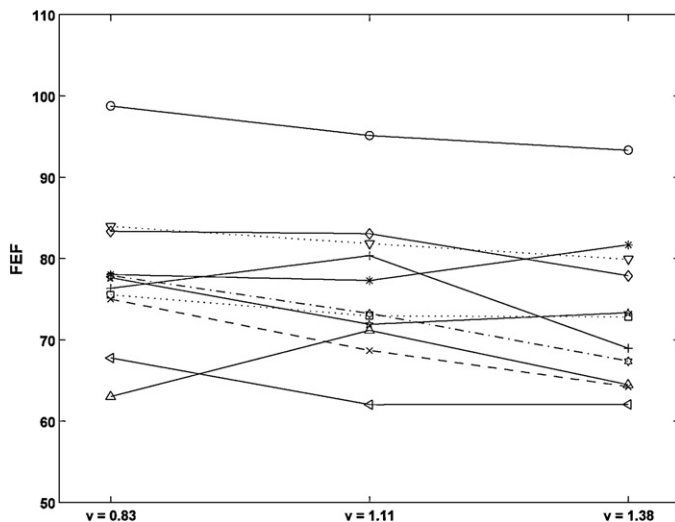


Fig. 2. FEF in relation to the three speed conditions. Individual trends in FEF are plotted for all participants ( $N = 11$ ).

#### 2.4. Statistical analysis

Data were analyzed with non-parametric tests. To evaluate the effect of speed at equal power output on the propulsion characteristics a Friedman Test was performed ( $p < 0.05$ ). When a significant difference was found, Wilcoxon Signed Rank Tests with adjusted  $p$ -values (Bonferroni correction,  $p < 0.017$ ) were performed to identify which speed conditions differed from another.

Wilcoxon Signed Rank Tests were performed to evaluate the effect of the method to impose power on the propulsion characteristics. Level of significance was set at  $p < 0.05$ .

### 3. Results

#### 3.1. Subjects

Due to a technical problem during the measurements of one subject, data of only 11 subjects could be used for data analysis. Subjects' characteristics were (mean  $\pm$  SD): age  $29 \pm 4$  years, height  $1.79 \pm 0.08$  m and body mass  $79 \pm 16$  kg ( $N = 11$ ).

#### 3.2. Effect of forced speed

Although we intended to apply a constant power by the pulley system, a small but significant difference in power output was found between the speed conditions (mean difference 1.8 W, effect size 1.1,  $p = 0.01$ , Table 1). At the lowest speed the power output was lower compared to the two faster speeds. The applied forces did not differ between speed conditions; only FEF (Fig. 2) differed between speed conditions ( $p = 0.02$ ). A higher effectiveness of force application (expressed as the fraction of effective force) was observed while propelling at lower velocity. Of the timing variables, cadence was constant over the speed conditions, whereas relative PTpC and push time decreased with increasing speed ( $p < 0.01$ ). Additionally, push angle increased with increasing speed ( $p < 0.01$ ).

#### 3.3. Effect of method to impose power

No significant differences were found for  $PO_{\text{performed}}$  for the 2 methods, but PTpC was slightly higher for propelling up the incline at 2.5 and 4% ( $p < 0.05$ ), while recovery time was consequently longer for propelling against the resistance of the pulley system. The latter was however only significant at the 4% condition

( $p = 0.03$ ). No significant differences were found for FEF (Fig. 3) or for the other force variables (Table 2).

### 4. Discussion

The purpose of this study was to investigate the influence of workload setting on the force and timing characteristics in handrim wheelchair propulsion in a group of subjects, propelling a handrim wheelchair on a motor driven treadmill under various conditions. The results provide important insight into the association between propulsion technique and speed (at constant power output) as well as between propulsion technique and method to impose power at various power levels.

#### 4.1. Effect of forced speed

The findings of the effect of speed, at the same power output, only partly support the hypothesis that the forced effect of a higher speed has an influence on the propulsion technique variables. It was found that for a higher forced speed, the timing variables were different although force variables were not.

It was intended to apply a constant  $PO_{\text{external}}$  by the pulley system (25 W); however the  $PO_{\text{performed}}$  was lower for the  $0.83 \text{ ms}^{-1}$  condition. At the lower speed the push frequency was lower. As a result the subjects might have sat more stable in the wheelchair with less oscillation of the trunk and less arm movement, lowering the drag force. Therefore the  $PO_{\text{performed}}$ , calculated from the measurement wheel, could have been lower than intended. Additional statistical analyses, excluding the lowest speed condition (Wilcoxon Signed Rank Test), showed no different results, except for push angle, which was not different between the two higher speed conditions.

The effectiveness of wheelchair propulsion decreased from 78.0% at  $0.83 \text{ ms}^{-1}$  to 73.7% at  $1.38 \text{ ms}^{-1}$ , which is consistent with findings from other studies [12,24,35]. However, per definition a higher FEF is not always better, since higher mechanical loads at the shoulder [36] and lower mechanical efficiencies [37] were found when propelling with a forced higher FEF based on feedback. In the current study the lower FEF is an indication that when propelling with higher velocities, but with equal power output, it seems even more difficult to apply the force in a tangential direction. The lower FEF apparently is an adaptive mechanism of the higher hand coupling speed and motion required at the higher yet less forceful coasting conditions. In wheelchair propulsion, an increase in velocity shortens the time for force application. Applying more force per push, extending the push angle or shortening the recovery time and therefore increasing cadence can counterbalance this. However, in this study the external power output was the same, leading to a lower resisting force with the higher speed. The findings of this study showed that the subjects did increase the push angle and were able to overcome the lower resistance at the higher speed with almost the same force. The force was however applied during a shorter push time, which is comparable to the results of Veeger et al. [24] who studied wheelchair propulsion on an ergometer.

#### 4.2. Effect of method to impose power

The findings for the method to impose power do not support the hypothesis that riding on a slope leads to different propulsion technique variables compared to propelling against the resistance of a pulley system at the same power output and speed. The expectation that force application was different when propelling on a slope was not confirmed. The significant differences in push time per cycle time and recovery time were rather small ( $p > 0.03$ ) and could be a coincidence. Basically there are no differences; the slope and gravity did not alter the force application and timing, although

**Table 1**  
Effect of speed on wheelchair propulsion ( $N = 11$ , able-bodied subjects): median (IQR) of the propulsion characteristics and the results of the Friedman two-way analysis of variance tests.

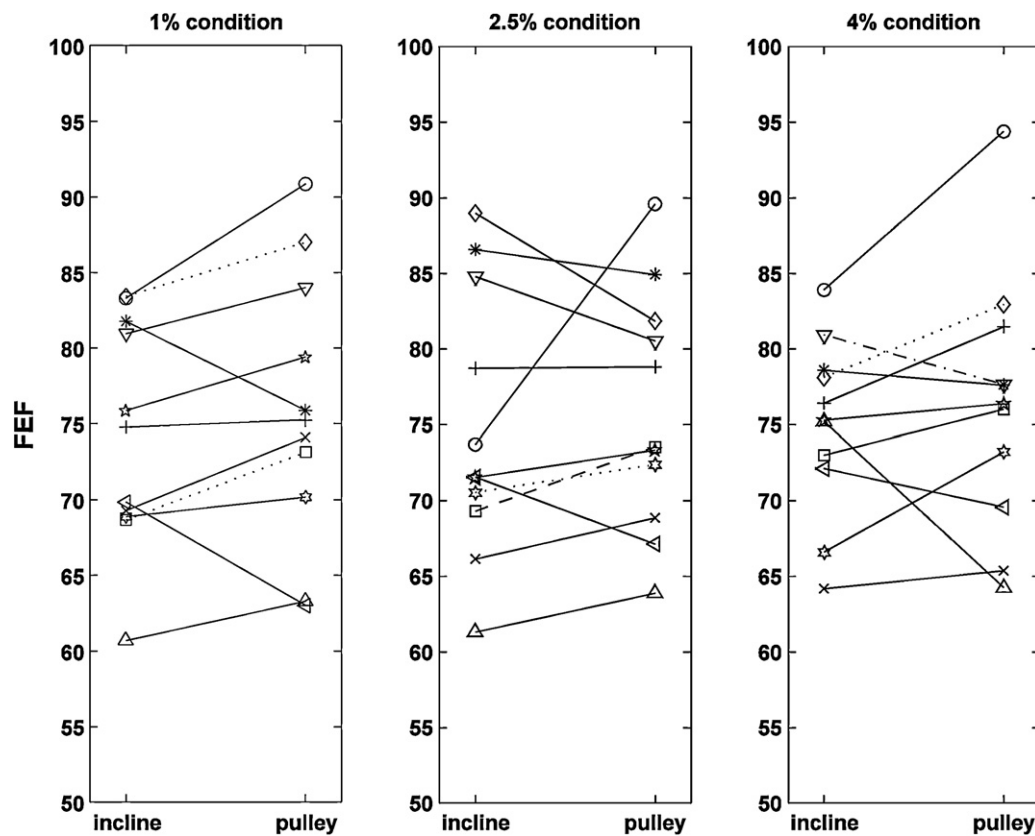
|                             | 0.83 ms <sup>-1</sup> | 1.11 ms <sup>-1</sup> | 1.38 ms <sup>-1</sup> | <i>p</i>           |
|-----------------------------|-----------------------|-----------------------|-----------------------|--------------------|
| PO <sub>performed</sub> [W] | 27.9 (27.4–28.2)      | 29.7 (28.2–30.3)      | 29.7 (28.9–30.9)      | 0.01 <sup>a</sup>  |
| Work [J]                    | 35.5 (26.4–37.5)      | 32.7 (26.0–36.9)      | 30.1 (27.8–36.0)      | NS                 |
| FEF [%]                     | 77.6 (75.0–83.4)      | 73.3 (71.2–81.8)      | 72.8 (64.5–79.9)      | 0.02 <sup>b</sup>  |
| $F_{\text{tot}}$ [N]        | 52.3 (49.5–68.5)      | 52.6 (45.3–62.1)      | 49.3 (44.6–56.2)      | NS                 |
| $F_{\text{tan}}$ [N]        | 44.6 (41.0–58.1)      | 44.5 (40.2–55.8)      | 41.2 (37.6–50.5)      | NS                 |
| $F_{\text{rad}}$ [N]        | 25.7 (22.6–30.4)      | 21.7 (16.7–25.8)      | 21.8 (12.8–29.0)      | NS                 |
| $F_{\text{lat}}$ [N]        | −7.5 (−13.8 to −3.5)  | −8.5 (−12.8 to −4.8)  | −8.0 (−12.3 to −4.1)  | NS                 |
| Cadence [pushes/min]        | 50 (46–59)            | 53 (46–62)            | 55 (49–64)            | NS                 |
| PTpC [%]                    | 45.4 (43.2–50.9)      | 39.8 (36.6–41.8)      | 34.1 (31.1–35.9)      | <0.01 <sup>c</sup> |
| Push time [s]               | 0.50 (0.46–0.63)      | 0.40 (0.36–0.50)      | 0.35 (0.30–0.38)      | <0.01 <sup>c</sup> |
| Recovery time [s]           | 0.58 (0.54–0.79)      | 0.68 (0.60–0.75)      | 0.68 (0.65–0.84)      | NS                 |
| Push angle [°]              | 75.5 (70.1–95.6)      | 81.4 (72.3–99.8)      | 90.8 (74.9–95.2)      | <0.01 <sup>a</sup> |

IQR, interquartile range; PO<sub>performed</sub>, performed power output; FEF, fraction of effective force;  $F_{\text{tot}}$ , total force;  $F_{\text{tan}}$ , tangential force;  $F_{\text{rad}}$ , radial force;  $F_{\text{lat}}$ , mediolateral force; PTpC, push time per cycle; NS, not significant.

<sup>a</sup> Wilcoxon test showed significant differences between 0.83 ms<sup>-1</sup> and 1.11 ms<sup>-1</sup> and between 0.83 ms<sup>-1</sup> and 1.38 ms<sup>-1</sup>,  $p < 0.017$ .

<sup>b</sup> Wilcoxon test showed significant difference between 0.83 ms<sup>-1</sup> and 1.38 ms<sup>-1</sup> and between 1.11 ms<sup>-1</sup> and 1.38 ms<sup>-1</sup>,  $p < 0.017$ .

<sup>c</sup> Wilcoxon test showed significant differences among all speed conditions,  $p < 0.017$ .



**Fig. 3.** FEF in relation to the method to increase power. Individual trends in FEF are plotted for all three comparisons for all participants ( $N = 11$ ).

the wheelchair-user system had a changed orientation in space. The variable reaction of the subjects might have been caused by the subjects' anthropometry in combination with the fixed wheelchair.

#### 4.3. Experimental considerations

Though we intended to use the pulley system to apply a constant power, the actual power output as measured with the rims was slightly higher than the predetermined power output on the basis of the drag test. This is in agreement with previous research from van der Woude et al. [26], where it was stated that during the drag test, where the subject is sitting immobile in the wheelchair, the measured drag force is likely to be somewhat underestimated, for

instance due to body weight shifts and deviations from a straight course.

The subjects in this study were non-experienced able-bodied subjects. It was expected that this group would respond relatively homogeneously to wheelchair exercise, since they were all inexperienced and had no restriction due to disability. However, as it turned out, the naïve users reacted differently to the new task. Some subjects showed an increase in the propulsion technique variables while others showed a decrease (i.e. Figs. 2 and 3). These differences are not uncommon. For example, Veeger et al. [24] found large intra-individual differences. On the other hand it is suggested that the propulsion technique is defined by the constraints of the musculoskeletal system [36] and therefore it is assumed that



**Table 2**  
Effect of the method to impose power ( $N = 11$ , able-bodied subjects, belt speed =  $1.11 \text{ ms}^{-1}$ ): median and interquartile range of the propulsion characteristics and results of the Wilcoxon Signed Rank tests.

|                             | 1%                  |                     |    | 2.5%                  |                      |      | 4%                   |                      |      |
|-----------------------------|---------------------|---------------------|----|-----------------------|----------------------|------|----------------------|----------------------|------|
|                             | Incline             | Pulley              | p  | Incline               | Pulley               | p    | Incline              | Pulley               | p    |
| PO <sub>performed</sub> [W] | 22.1 (19.7–26.0)    | 22.6 (20.6–27.1)    | NS | 34.8 (32.9–41.1)      | 34.5 (32.9–40.9)     | NS   | 50.9 (45.8–58.8)     | 48.6 (44.9–60.5)     | NS   |
| Work [J]                    | 26.8 (21.0–33.9)    | 27.0 (21.4–30.5)    | NS | 40.5 (37.4–48.0)      | 39.9 (36.3–55.7)     | NS   | 57.3 (43.9–64.7)     | 56.0 (50.3–67.1)     | NS   |
| FEF [%]                     | 74.8 (68.9–81.8)    | 75.2 (70.2–84.0)    | NS | 71.6 (69.3–84.8)      | 73.5 (68.9–81.9)     | NS   | 75.3 (72.0–78.6)     | 76.4 (69.6–81.5)     | NS   |
| F <sub>tot</sub> [N]        | 40.0 (36.6–55.0)    | 40.3 (37.4–50.2)    | NS | 60.1 (53.3–66.0)      | 59.7 (50.0–70.8)     | NS   | 77.9 (75.7–87.3)     | 78.5 (74.0–88.4)     | NS   |
| F <sub>tan</sub> [N]        | 33.9 (28.6–47.6)    | 31.8 (29.4–42.9)    | NS | 48.3 (42.9–54.9)      | 48.4 (43.5–58.4)     | NS   | 65.1 (60.6–69.1)     | 66.9 (59.8–77.2)     | NS   |
| F <sub>rad</sub> [N]        | 19.3 (14.3–27.6)    | 18.3 (11.3–31.5)    | NS | 24.5 (15.9–36.7)      | 26.9 (19.2–35.9)     | NS   | 37.1 (29.0–44.7)     | 31.3 (24.0–41.7)     | NS   |
| F <sub>lat</sub> [N]        | –4.8 (–8.0 to –4.3) | –5.1 (–7.9 to –1.7) | NS | –11.0 (–15.8 to –4.1) | –6.9 (–10.4 to –5.1) | NS   | –5.7 (–18.6 to –4.0) | –5.9 (–14.0 to –3.8) | NS   |
| Cadence [pushes/min]        | 53 (46–59)          | 50 (45–58)          | NS | 52 (47–58)            | 50 (45–59)           | NS   | 53 (49–64)           | 53 (46–65)           | NS   |
| PTpC [%]                    | 41.0 (35.0–47.3)    | 36.3 (34.2–42.7)    | NS | 42.7 (38.6–47.0)      | 43.6 (36.6–45.9)     | 0.04 | 44.9 (43.1–49.3)     | 44.5 (41.0–48.3)     | 0.05 |
| Push time [s]               | 0.45 (0.41–0.49)    | 0.45 (0.43–0.46)    | NS | 0.49 (0.40–0.54)      | 0.47 (0.44–0.52)     | NS   | 0.48 (0.42–0.55)     | 0.47 (0.41–0.55)     | NS   |
| Recovery time [s]           | 0.71 (0.59–0.84)    | 0.74 (0.62–0.86)    | NS | 0.67 (0.52–0.79)      | 0.65 (0.55–0.85)     | NS   | 0.58 (0.45–0.67)     | 0.59 (0.48–0.76)     | 0.03 |
| Push angle [°]              | 92.4 (82.0–96.1)    | 89.9 (86.7–93.6)    | NS | 98.8 (85.1–106.3)     | 96.4 (89.3–100.8)    | NS   | 95.5 (81.8–106.6)    | 93.5 (84.1–106.5)    | NS   |

PO<sub>performed</sub>: performed power output; FEF, fraction of effective force; F<sub>tot</sub>, total force; F<sub>tan</sub>, tangential force; F<sub>rad</sub>, radial force; F<sub>lat</sub>, mediolateral force; PTpC, Push time per cycle; NS, not significant.

persons implicitly optimize task performance by making small changes in their technique. Force magnitude and movement velocity are apparently instinctively regulated to overcome the new requirements in both setups, whereas the relatively low intensity of the task here might imply only a small penalty for deviations from the ideal technique.

The results found in this study will relate well to persons with a paraplegia or wheelchair dependent persons due to leg amputation. For transferring results to the elderly and persons with a tetraplegia, one has to keep in mind that due to loss of muscle force the adaptations to changing propulsion conditions might be different. Further studies investigating this will have to be conducted.

The wheelchair used in this study was a standard wheelchair which likely was not as tippy as wheelchair users' would have setup their own chair. Another limitation is that the wheelchair was not adjusted to the subjects, which could result in disadvantageous force application, as found in a recent study for wheelchair propulsion [38]. However, the effect is constant within the person and the different experimental conditions. The suboptimal wheelchair-user interface will only have an influence on the absolute values of the propulsion technique parameters.

## 5. Conclusion

When propelling a wheelchair at equal power output, but with different speeds, speed itself has an influence on the timing variables of the propulsion technique and should therefore be considered when analyzing propulsion technique. However, at the same power output and speed, propulsion technique variables do not differ between propelling on an inclined treadmill with inclines up to 4°, or when propelling on a level treadmill against a resistance applied by a pulley system.

Researchers and clinicians must be aware of testing and evaluation conditions/methods that may differently affect propulsion technique parameters despite an overall constant power output.

## Funding

The authors state that no financial support was received for this work.

## Ethical approval

The study was approved by the ethical committee of the canton Luzern, Switzerland and is in accordance with the ethical standards in the 1964 Declaration of Helsinki.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.medengphy.2012.04.017>.

## Conflict of interest

The authors confirm that there is no conflict of interest in relation to this work.

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